


Research Article

Landings of *Sphyrna zygaena* (Linnaeus, 1758) in northern Peru indicate a lack of adult specimens

Katicsa Natalie De La Cruz Barrueto¹ , Kenyi Kaneshima González¹ 

Zoila Gladis Culquichicón Malpica² 

Alvaro Edmundo Tresierra Aguilar²  & Bilmia Veneros Urbina² 

¹Professional School of Fisheries Biology, Universidad Nacional de Trujillo, Trujillo, Perú

²Department of Fisheries, Universidad Nacional de Trujillo, Trujillo, Perú

Corresponding author: Zoila Gladis Culquichicón Malpica (zculquichiconm@gmail.com)

ABSTRACT. A commercial fishery for the smooth hammerhead shark (*Sphyrna zygaena*) exists in the waters off northern Peru. Although international and domestic norms regulate this species, adult specimens are becoming rare. Monthly visits to four ports in the La Libertad region were made to measure *S. zygaena* landings and understand the present state of the fishery. We found that 92% of the specimens landed were juveniles or younger and that 10% of the original biomass remains in the fishery. This highlights that stricter regulations such as protecting breeding areas, establishing a legal catch length, and limiting the catch volume and fishing season are urgently needed to maintain a sustainable fishery.

Keywords: *Sphyrna zygaena*; smooth hammerhead shark; fisheries management; population structure; overfishing; Peru

INTRODUCTION

The smooth hammerhead shark, *Sphyrna zygaena* (Linnaeus, 1758), is a highly migratory predator that is usually found near the coasts of South America, North America from the Caribbean north to Nova Scotia, Europe and Africa (UN 2019). *S. zygaena* reproduces in estuaries, feeds on at least 20 different prey species, and has a trophic level of 4.6. Its diet depends on size, sex, and location. A major component of its diet includes cephalopods such as *Doritheuthis gahi* (d'Orbigny, 1835), *Mastigoteuthis denta* (Hoyle, 1904), *Lolliguncula diomedea* (Hoyle, 1904) and *Dosidicus gigas* (d'Orbigny, 1835). Two breeding areas were identified in the ocean near northern Peru due to the high nutrient content of the area. (Ochoa-Díaz 2009, Gonzalez-Pestana et al. 2017, Mejía et al. 2022).

Peru is a commercial exploiter of *S. zygaena* (Gonzalez-Pestana et al. 2016), where it is known and

consumed locally as "tollo". It is Peru's third most caught shark species (Gonzalez 2014). The *S. zygaena* catch peaked in 1998, with 1200 t landed, which fell to >250 t in 2000, increased to 700 t in 2003, and remained stable at about 500 t until 2016. In 2016, the Peruvian government established a management scheme with a fishing season and a catch volume quota between 460 and 480 t. Follow-up on catch volume quota has been difficult due to problems with monitoring landings. However, since 2016, the total landing estimate has remained below 500 t. Since 2016, extraction is prohibited between January 1 and March 10 (Ghezzi-Solis 2016, Chicoma-Lúcar 2021, IMARPE 2022).

The reproductive biology of *S. zygaena* and other sphyrnids makes populations vulnerable to unregulated fishing because they grow slowly, mature at a late age, and have a low natural rate of population increase (Tresierra & Culquichicón 1993). For this reason, all *Sphyrna* spp. are listed in Appendix II of the Convention

on International Trade in Endangered Species of Wild Fauna and Flora (CITES) treaty, and eight sphyrnids are listed as vulnerable, threatened, or endangered by the International Union for Conservation of Nature (IUCN). Currently, *S. zygaena* is listed as vulnerable with a decreasing population by the IUCN (Gonzalez-Pestana et al. 2016, CITES 2023, IUCN 2023).

Because maintaining sustainable fisheries is based on data-driven cooperation between policymakers, law enforcement, and marine biologists, we report on the population and size distribution of *S. zygaena* landings in the La Libertad region of Peru to understand the current population dynamics of this fishery.

MATERIALS AND METHODS

Between March and September 2022, once-monthly surveys were conducted in the fishing ports of Pacasmayo ($7^{\circ}23'53''\text{S}$, $79^{\circ}34'16''\text{W}$), Puerto Malabrigo ($7^{\circ}41'46''\text{S}$, $79^{\circ}26'10''\text{W}$), Salaverry ($8^{\circ}13'26''\text{S}$, $78^{\circ}58'52''\text{W}$), and Puerto Morín ($8^{\circ}23'56''\text{S}$, $78^{\circ}53'49''\text{W}$), all located in the La Libertad region of northern Peru (Fig. 1). A persistent La Niña was present during this time, resulting in lower-than-average sea surface temperatures (NOAA 2023). No selectivity analysis was performed because the fishers used gillnets that did not have a large range in mesh size (20 to 25 cm). Landed specimens of *S. zygaena* were identified according to Romero-Camarena (2018).

Headless specimens were measured from the fifth-gill slit to the tip of the caudal fin (headless length, HL) using a measuring tape. Likewise, total length (TL, distance from the tip of the snout to the tip of the caudal fin) was measured for intact specimens (Fig. 2). To correlate HL and TL, 10 additional intact *S. zygaena* specimens that were not included in the population study were physically examined for HL and TL after the study period. Regression analysis to relate HL to TL was calculated using R version 4.3.0 (2023-04-21) (R Core Team 2021). This regression was used to determine the calculated TL (cTL) for all headless specimens in this study. The Shapiro-Wilk test for normality, Tukey's fence for outliers, and the Mann-Whitney U test were used for cTL data, with a statistical significance of $P < 0.05$.

The FISAT II computer program (FAO 2023) was used to calculate the population statistics of the studied *S. zygaena* fishery. The input data was the TL or cTL of all observed landings of *S. zygaena* with a histogram interval of 3 cm. The method described by Bhattacharya

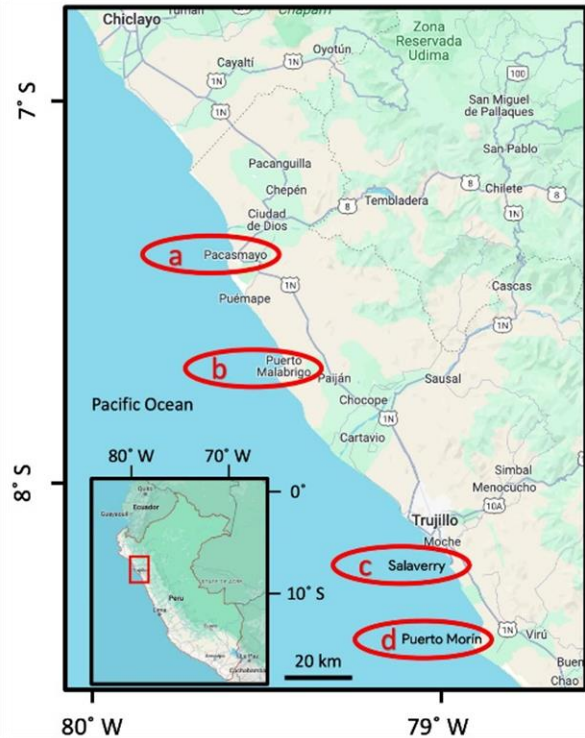


Figure 1. Map of sampling area showing the four ports surveyed in this study. Inset denotes location within Peru. From north to south, these ports are as follows: a) Pacasmayo, b) Puerto Malabrigo, c) Salaverry, and d) Puerto Morín.

(1967) separated different population groups in the size histogram. Statistics calculated by FISAT II included asymptotic total length (L_{∞}), constant growth rate (k), age at which fish length is calculated to be zero (t_0), number of modes used in the growth curve divided by the total number of modes (R_n), fishing mortality (F), total mortality (Z), natural mortality (M), exploitation ratio (E), recruitment pattern, probability of capture as a function of total length, yield isopleth, and relative yield per recruit and average biomass per recruit. L_{∞} was estimated using the maximum cTL (183 cm) as a seed and the Taylor equation, where $L_{\infty} \times 0.95$ equals the maximum TL. Asymptotic total mass (W_{∞}) was calculated using $W_{\infty} = a(L_{\infty})^b$, where $a = 0.0000016$ and $b = 3.2$. Growth curves were calculated using von Bertalanffy's growth equations for length and weight, using data obtained from FISAT II. The equation for length is $L = 192.63(1 - e^{-0.41(t+0.23)})$. The equation for mass is $W = 32.75(1 - e^{-0.41(t+0.23)})^{3.2}$. The M rate was calculated using the von Bertalanffy formula, assuming a temperature of 16°C (Pauly 1984, Tresierra et al. 1995).

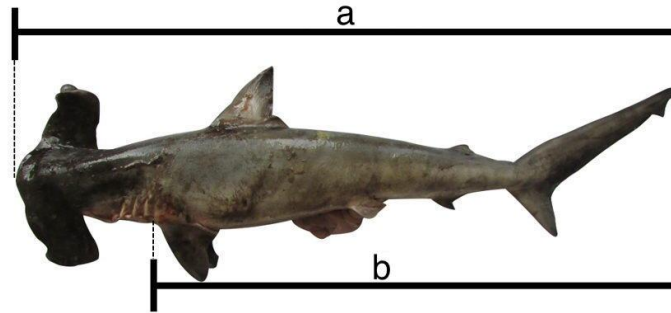


Figure 2. Measurement of shark length. Intact landed specimens were measured from the snout's tip to the caudal fin's tip (a). Headless specimens were measured from the fifth-gill slit to the tip of the caudal fin (b).

RESULTS

In Pacasmayo, the surveys in March and April yielded 4 and 62 *S. zygaena* specimens, respectively. In Salaverry, the largest fishing port in La Libertad, surveys in May, June, July, and September yielded 159, 63, 17, and 2 *S. zygaena* specimens, respectively. None of the other surveys observed landings of *S. zygaena*.

Since fishers rapidly decapitated, eviscerated, and sold landed specimens, TL was measured directly for 58 *S. zygaena* specimens, and only HL was measured for the remaining 249. To calculate TL from headless specimens, 10 additional and independent specimens that were not included in the study were examined for both HL and TL (Suppl. data, Fig. 3). Regression analysis showed that HL strongly predicted TL ($R^2 = 0.97$, $F(1,8) = 308.44$, $P < 0.001$. $\beta = 1.32$, $P < 0.001$, $\alpha = 2.97$, $P = 0.574$). The Shapiro-Wilk test did not show a significant deviation from normality for residuals, $W(10) = 0.85$, $P = 0.059$). The independent variable was not heteroskedastic according to the Breusch-Pagan test ($P = 1$). Small changes in the slope or intercept of the calculated regression line did not alter the conclusions of this paper.

Length data was rounded to the nearest centimeter. Salaverry cTL ranged from 78 to 183 cm, with a median of 92 cm and a skew toward smaller specimens (Shapiro-Wilk, $W(241) = 0.85$, $P < 0.001$). The longest cTL qualifies as an outlier using Tukey's fence. Pacasmayo cTL ranged from 63 to 121 cm with a median of 80 cm. Like Salaverry, there was a skew toward smaller specimens (Shapiro-Wilk, $W(66) = 0.9$, $P < 0.001$). Combining all cTL data from the study, we observe a skew toward smaller specimens (Shapiro-Wilk $W(307) = 0.88$, $P < 0.001$): most specimens were between 83 and 119 cm with a median of 91 cm and a mode of 90 cm.

Although there was a statistically significant difference in cTL between ports (Mann-Whitney U,

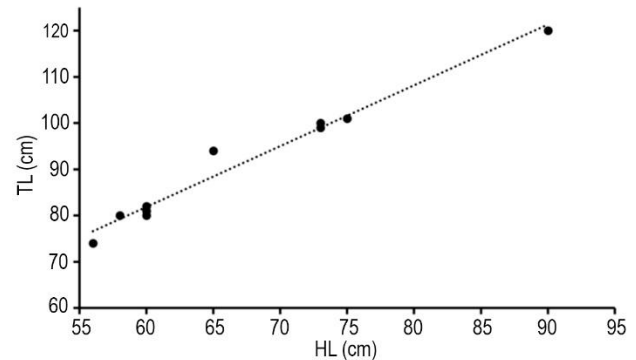


Figure 3. Regression plot correlating the distance between the fifth-gill slit and the tip of the caudal fin (headless length, HL) and the distance between the tip of the snout and the tip of the caudal fin (total length, TL) for 10 specimens of *S. zygaena*. The measurements are highly correlated ($R^2 = 0.97$). Each point represents the TL and HL measurements of a single specimen.

$P < 0.001$), population statistics were calculated on combined fishery data because the species is highly mobile (UN 2019), the catches were in different months for different ports, fishing locations changed, fishing boats sometimes did not depart from the same port they left, and the two ports were rather close together. Thus, it is likely that the same fishery was being sampled.

To visualize landed *S. zygaena* cTL, we created a histogram (Fig. 4). Upon inspection of the data, five age groups were determined (Bhattacharyya 1967). From these data, it was also possible to calculate additional population statistics using FiSAT II (FAO 2023), described in Table 1. From the length and weight growth curves (Fig. 5), we observe that the length of *S. zygaena* increases rapidly until it reaches an inflection point at approximately one year of age, where the growth rate decreases through the juvenile and adult stages. The weight growth curve has two inflection points, one at 1 year and another at 5 years. Rapid

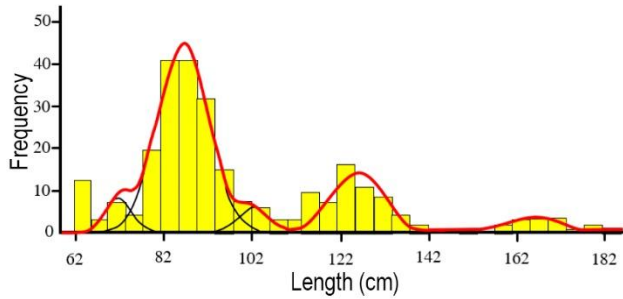


Figure 4. Histogram of *S. zygaena* total length landed between March and September 2022 in Pacasmayo and Salaverry. The bin width is 3 cm. The histogram skews toward smaller specimens. Five different population groups are observed (red lines).

weight gain occurs between 1 and 5 years of age. Breeding occurs in October, and recruitment peaks between May and July (Fig. 6). The small apparent increase in November is likely an artifact, since the histogram is normally distributed (The Shapiro-Wilk test did not show a significant departure from normality, $W(12) = 0.91$, $P = 0.245$). The M rate was 0.46 yr^{-1} , a value considered high for this species, as Lopez-Martinez et al. (2020) and Mejía et al. (2022) reported values between 0.23 and 0.39. Given this value, death from natural causes was 37.5%

Furthermore, statistics on the state of the fishery were calculated. The Z rate was estimated to be 2.18 yr^{-1} , with a 95% confidence interval from 1.66 to 2.71 (Jones & Van Zalinge 1981). The difference between Z and M gives F, which is 1.72 yr^{-1} . The L_{25} , L_{50} , and L_{75} probabilities of capture were 82.3, 100.7, and 119.1, respectively (Fig. 7). We also find that this mortality is not evenly distributed along lengths (Fig. 8), with the highest F occurring near maximum length and between 83 and 91 cm. The yield isopleth (Fig. 9) was used to estimate an E of 0.79. Applying this rate to the relative yield per recruit plot (Fig. 10), we calculate the maximum sustainable yield at an E of 0.695, an optimal yield of 0.61, and critical biomass at an exploitation rate of 0.37. Examining the curves in Figure 9 indicates that approximately 10% of the original biomass of the fishery remains, given the present estimate of E.

DISCUSSION

Throughout the study period, no specimen greater than 200 cm was landed, the minimum length for sexual maturity (Castañeda 2001, Nava & Márquez-Farías 2014). Almost all (92%) the landings analyzed in this study were neonates (50-70 cm) and juveniles (71-150 cm), locally sold as “baby tollo” at fishmongers, which

Table 1. Population statistics of *S. zygaena* in the La Libertad region of Peru. L_{∞} : asymptotic total length, k : constant growth rate, t_0 : age at which fish length is calculated to be zero, R_n : number of modes used in the growth curve divided by the total number of modes, and W_{∞} : asymptotic total mass.

Parameter	Value with units
L_{∞}	192.63 cm
k	0.41 yr^{-1}
t_0	-0.23 years
R_n	0.341
W_{∞}	32.75 kg

is troubling because a larger catch of juvenile organisms may mean that a significant number of organisms no longer contribute to population recruitment, which has consequences for long-term population stability.

However, this was not the case for a study at the turn of the century in which specimens as large as 340 cm were observed (Castañeda 2001, Nava & Márquez-Farías 2014, Mejía et al. 2022). A subsequent study in Peru published in 2021 observed a maximum length of 294 cm (Acuña 2021). However, previous studies also observed a tendency toward smaller specimens, somewhat consistent with *S. zygaena* behavior, as it remains in coastal areas during the first years of life (Bolaño-Martínez 2009), which would facilitate its capture (Carrera-Fernández 2011) and may have been more prevalent during the time of the present study due to below-average sea surface temperatures. Likely explanations for the lack of adult specimens in this study include (1) movement of adults and larger specimens to other locations not reached by the fishing fleet due to the La Niña or other factors, (2) changes in social segregation and recruitment areas, (3) changes in fishing areas, (4) high levels of fishing mortality that have completely stripped the population of older individuals, and (5) other human-related pressures, such as pollution, ghost fishing, vessel traffic, and climate change (Pierce & Charles 2022).

S. zygaena was landed at only two of the four ports studied. There are three likely reasons for this. First, Morín and Malabrigo have smaller fleets, with Salaverry accounting for about half of the total catch in the La Libertad region. Second, other authors have also suggested that this is due to seasonal migration of *S. zygaena* to cooler waters in summer and warmer waters in winter, which bypassed Morín and Malabrigo, as long-duration La Niña conditions in the Pacific Ocean

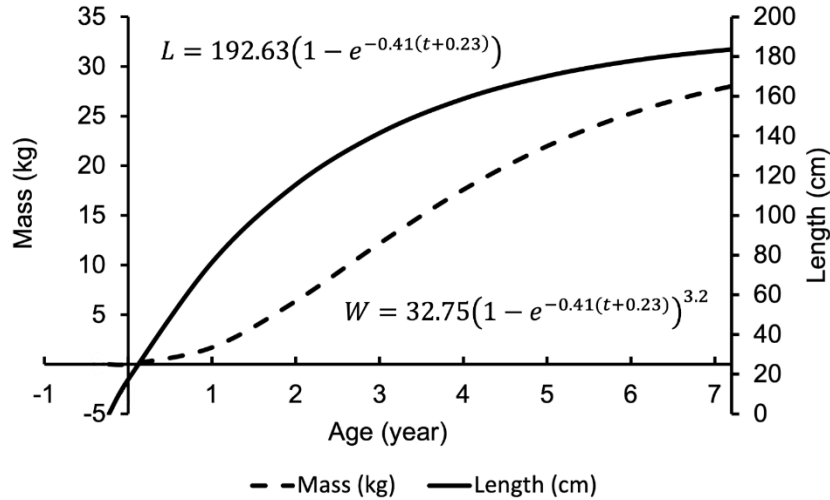


Figure 5. Growth curves for length (solid line) and mass (dashed line) for *S. zygaena* landed between March and September 2022 in Pacasmayo and Salaverry.

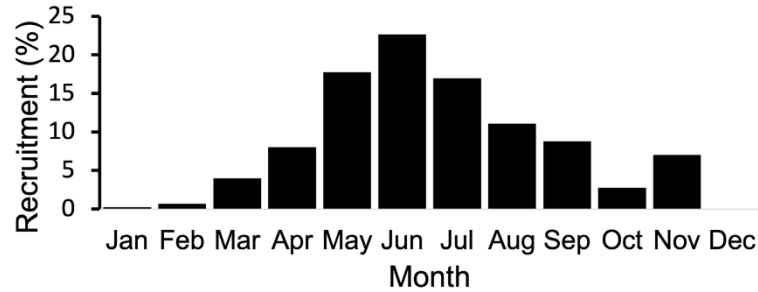


Figure 6. Recruitment pattern for *S. zygaena* landed between March and September 2022 in Pacasmayo and Salaverry.

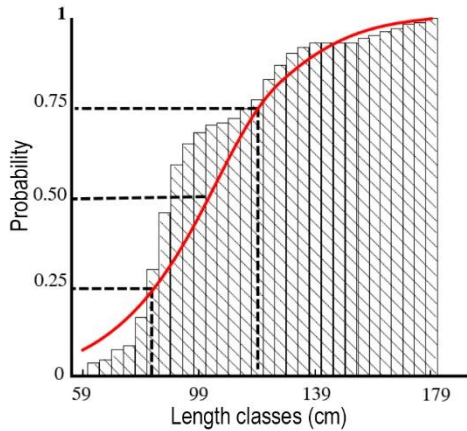


Figure 7. Probability of capture of *S. zygaena* as a function of total length for specimens landed between March and September 2022 in Pacasmayo and Salaverry.

dominated between September and mid-November 2022 (NOAA 2023). Third, personal communication with the fishers from the four ports indicated that 2022

was a poor year for fishing. Fishers in Puerto Morín migrated north, and those in Puerto Malabrigo focused on other species.

Because of the absence of longer specimens in the present study, the population statistics in Table 1 probably underestimate L_{∞} and overestimate k . A report on *S. zygaena* in Baja California calculated an L_{∞} of 349 cm and k of 0.16 for females and an L_{∞} of 338 cm and k of 0.18 for males, for example (Morán Villatoro 2018). Other research on *Sphyrna* spp. shows a similar trend, with L_{∞} between 220 and 350 cm, k between 0.11 and 0.18, and t_0 between -2.86 and -0.63 years (Anislado & Robinson 2001, Piercy et al. 2010, Zarate-Rustrián 2010). An additional review of several studies of *S. zygaena* populations suggested a TL L_{∞} and k of 313.85 cm and 0.10 for males, as well as 298.96 cm and 0.14 for females, respectively (Mejía et al. 2022). An inverse relationship exists between L_{∞} and k : as L_{∞} decreases, k increases, which was observed here. Although our results are not likely applicable to understanding populations of *S. zygaena* that do not

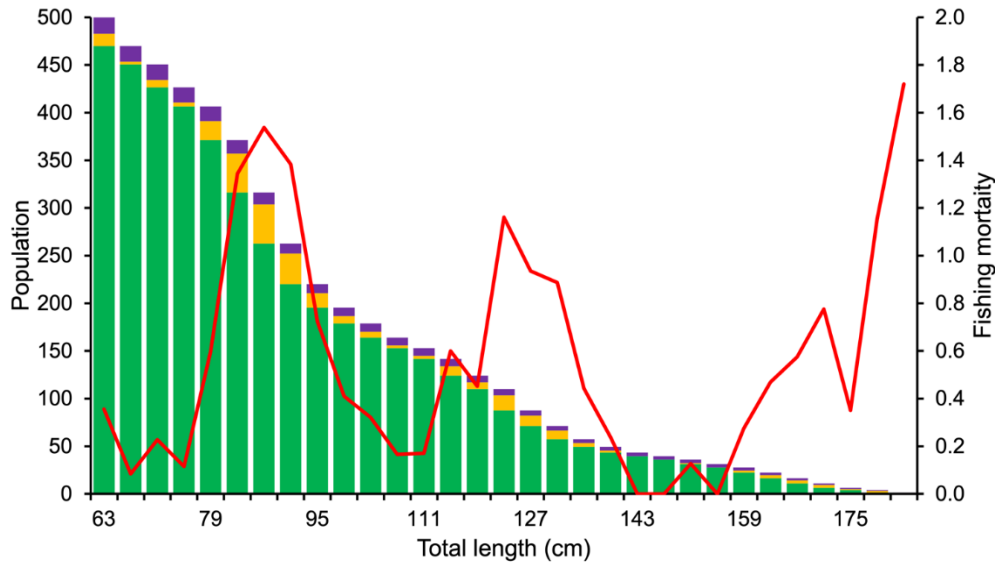


Figure 8. Mortality vs. total length for *S. zygaena* landed between March and September 2022 in Pacasmayo and Salaverry. Natural mortality (purple), fishing mortality (yellow), and remaining survivors (green) are represented for each length class. The red line also represents fishing mortality according to length.

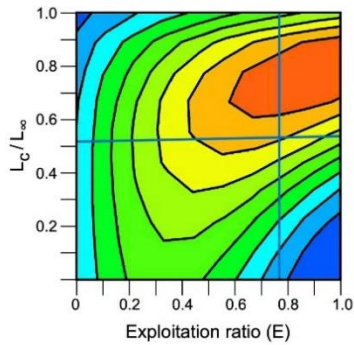


Figure 9. Yield isopleth plot for *S. zygaena* landed between March and September 2022 in Pacasmayo and Salaverry. The vertical axis is the ratio of the median capture length (L_c or L_{50}) to the infinite length (L_∞) while the horizontal axis is the exploitation ratio (E). The contour lines represent the response of yield-per-recruit to changes of length at first capture and exploitation rate. The blue horizontal and vertical lines represent the L_c/L_∞ and E determined in this study (0.52 and 0.79, respectively).

experience high fishing pressure levels, our results indicate that practically no individuals in the fishery reach the L_∞ calculated elsewhere or previously. Furthermore, the value of Z may be slightly overestimated, but the negative value of t_0 decreases this overestimation. Therefore, our results highlight how population statistics can be skewed when older specimens are absent.

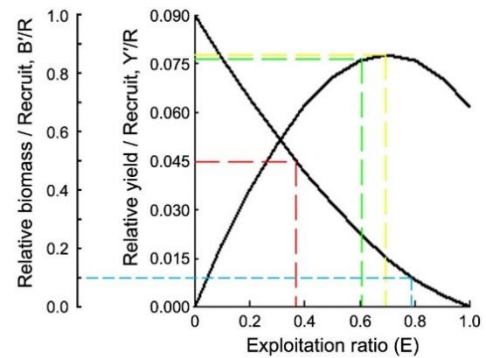


Figure 10. Beverton-Holt's relative yield per recruit and average biomass per recruit model for *S. zygaena* landed between March and September 2022 in Pacasmayo and Salaverry. E_{10} (green line), E_{50} (optimal sustainable yield, red line), and E_{max} (maximum sustainable yield, yellow line) are included. The blue line indicates the current situation.

Landings of *S. zygaena* were not evenly distributed throughout the study period; more than half of the specimens studied were landed in May. May and June also coincide with maximum recruitment (Fig. 6). These results may be explained by climatic patterns off the northern Peruvian coast. During the austral winter, the Pacific anticyclone creates strong winds that flow principally from the south and then veer westward, strengthening an upwelling of nutrients that enrich the food chain, enabling predators such as *S. zygaena* to

grow rapidly during these months. It is also likely that this yearly cycle is responsible for the February breeding season, enabling neonates to take advantage of this abundance.

The M calculated here was higher than that for other studies of *S. zygaena* populations (0.46 vs. 0.21-0.37 yr⁻¹) (Mejía et al. 2022), which must be considered for management plans (Giménez et al. 2011). Decreasing M could improve the sustainability of the fishery in the long term. Present legal protections include a fishing season and a catch volume quota, but additional protections have been recommended. One possible way to decrease M could include better management of estuaries, bays, and mangroves where *S. zygaena* commonly rears its young, where turbid, nutrient-rich water offers food and protection to neonates and juveniles (Zanella et al. 2009).

Additionally, the Ministry of Environment of Peru prepared a non-detriment report for this species, which concludes that landings for artisanal fisheries are mostly composed of neonates (50-70 cm) and juveniles (71-150 cm), leaving few specimens of reproductive age (Rodríguez-Pacheco 2016). To better manage the fishery, the report recommends the implementation of management measures such as improved fishery monitoring, closing the fishery during the reproductive season to improve recruitment, determination of a minimum legal catch length, establishment of access limits to the fishery, regulation of gillnet mesh size, and the encouragement of the use of more selective fishing gear (spinel). These measures are directed toward allowing more specimens to reach reproductive age before harvest. The report concludes that the maximum sustainable yield is 482 t per year with a maximum of 23 t of shark fins.

CONCLUSIONS

Comparing the results of this study with previous research conducted in recent decades indicates a possible decline in the adult population of *S. zygaena* in northern Peruvian waters, transforming the fishery to catching mainly neonates and juveniles, which may be due to fishing pressure or the adults moving to other locations. Additional research, such as including more specimens, sampling over a longer time that includes both La Niña and El Niño years, and sampling at more locations more frequently, may improve understanding of the changes occurring in and sustainable management of the fishery.

Data availability statement

A spreadsheet containing the regression of HL and TL of intact specimens and HL and cTL, month, and landing port of the sharks examined in this study is available as a Supplementary data set.

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Authorship

KNDeLaCB: Formal analysis, investigation, writing - original draft, writing - review and editing, Data Curation. KKG: investigation, writing - original draft, writing - review and editing, data curation. ZGCM: conceptualization, funding acquisition, formal analysis, methodology, project administration, resources, supervision, writing - review, and editing. AETA: funding acquisition, methodology, resources, validation. BVU: funding acquisition, methodology, resources.

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